Magnetic Tags

Field of the Invention

This invention relates to the field of magnetic tags for storing data, particularly but not exclusively to tags in which data is stored by reference to a combination of magnetic element characteristics.

Background

PCT publication number WO99/35610 describes tags and reader systems primarily intended for tags fabricated from magnetic material of low coercivity, with elements at different orientations, in which data is recorded primarily by means of the orientation of the elements with respect to each other. The described system assumes that the coercivities of the tag elements are all the same, and are very small compared to the interrogation field.

Co-pending application no. PCT/GB00/03092, which is incorporated herein by reference in its entirety, describes a reading system for decoding magnetic tags including tags according to the present invention.

Summary of the Invention

According to the invention, there is provided a magnetic tag for storing data, comprising at least one magnetic element configured such that the data is stored by reference to a combination of two or more characteristics associated with the or each element.

Advantageously, a first one of the characteristics can be used to identify or distinguish the elements from one another and a second one of the characteristics can be used to store data. One or more further characteristics can be used to store additional data.

There is no limit on the type of characteristic which can be used and it can be any measurable magnetic property or parameter such as location of an element or presence or absence of an element. The characteristics can include one or more

selected from element coercivity, element bias, element orientation, amplitude response of an element, response bandwidth, dependence of element switching field in response to the rate of change of an applied field, element switching speed, element location, maximum cross-field bias, permeability, Barkhausen response and resonant frequency.

The magnetic tag can comprise a plurality of magnetic elements, each of the magnetic elements being disposed in a different orientation by which it is distinguishable from the other elements and each having a magnetic bias member capable of assuming a plurality of states, wherein data is stored by the state assumed by the magnetic bias member. Further data can be stored by the orientation of each of the elements being selected from a set of possible orientations. Additional data can also be stored by arranging for one or more of the elements to exhibit a different coercivity and/or a different amplitude response from that of the other elements.

The magnetic tag can alternatively comprise a plurality of intersecting magnetic elements, each of the magnetic elements being disposed in a different orientation by which it is distinguishable from the other elements and each having a coercivity selected from a set of possible coercivities, whereby to store data. The relative orientations of the elements can be used to identify the elements and to store data, and the coercivities of the elements can be used to store further data.

Yet further, the magnetic tag can comprise a plurality of magnetic elements, each of the magnetic elements being disposed in a different orientation by which it is distinguishable from the other elements and each being located at one of a plurality of possible locations whereby to store data.

The magnetic tag can also comprise a plurality of magnetic elements, each of the magnetic elements being located at one of a plurality of possible locations and each having a coercivity which is selected from a set of possible coercivities, whereby to store data.

Brief Description of the Drawings

Embodiments of the invention will now be described by way of example with reference to the accompanying drawings in which:

Figure 1 illustrates a 40-bit programmable thin-film data tag;
Figure 2 illustrates a portion of a thin-film data tag in which data storage density is increased by varying the width of each element;
Figure 3 illustrates a portion of a thin-film data tag in which data storage density is increased by varying the relative orientation of the elements;
Figure 4 shows a 7-element coercivity-angle-encoded data tag;
Figure 5 shows a 7-element location-angle-encoded data tag; and
Figure 6 shows a 7-element coercivity-location-encoded data tag.

Detailed Description

Passive magnetic data tags in accordance with the invention comprise one or more magnetically active dipole elements. The primary constraints on data tag construction are:

1. Amount of data (number of bits)
2. Physical size
3. Reading method
4. Programmability

Within these constraints, there are many alternative arrangements that can achieve the same result. Some embodiments are particularly favourable, in terms of the tag construction and the complexity of the reading/decoding process, for example, those in which:

1. More than one property varies between elements, for example selected from orientation, bias, response amplitude (i.e. saturated dipole moment), coercivity and location (or presence/absence) of an element.
2. One parameter is used to distinguish the element, and one or more other parameters are used to store the data.
3. The number of bits of data per magnetic element is greatest.

The embodiments described below do not represent the ultimate data capacity of the tag. The data capacity can be maximised by using more elements, by varying more properties, and by increasing the resolution of the reading system to distinguish between more states, for example, closer orientations or similar amplitude. In general terms, the more complex the tag becomes, the less robust the reading system becomes. In the general case where there are n different elements, and m different states for each element, in total there are m^n different possible states. There are $2n$ ambiguities related to which way up the tag is, and which element is which, leading to $m^n/2n$ possible states. The achievable data density is about 100 bits of data.

A first example of the invention is described with reference to Figure 1. A plurality of magnetic elements 1-21 are arranged on a substrate 22, each at a different orientation, and each with a different bias field. The orientation is used to identify and distinguish the elements, and the bias state of each element is used to store data. Each element occupies a different position on the tag. In the simplest implementation, no information is stored in the position, coercivity or amplitude or by reference to any other properties.

Each element consists of a $9x9mm^2$ square of soft magnetic material, for example, Atalante™ thin film material (manufactured by IST of Zulte, Belgium, part number SPR97017A). This material has an "easy" axis of magnetisation, which provides a nominal orientation or direction for the element, or, in other words, the material exhibits a directional response to an applied magnetic field. Directly on top of each element is placed a layer of a hard magnetic material, for example, ferric oxide recording tape, with a coercivity of 24 kA/m, and a film thickness of $10\mu m$. This magnetic material is anisotropic, and the axis of magnetisation is aligned with that of the soft material.

The elements 1-21 are arranged on a square grid with a pitch of 10mm. Each element 1-21 is rotated to a different angle, as shown in the following table.

Element	Angle
1	0°
2	8°
3	16°
4	24°
5	32°
6	40°
7	48°
8	56°
9	64°
10	72°
11	80°
12	88°
13	96°
14	104°
15	112°
16	120°
17	128°
18	136°
19	144°
20	152°
21	164°

Table 1

The magnetic recording film can be in one of four states: unmagnetised; magnetised parallel to the nominal direction of the element; magnetised at 180° to the nominal direction of the element; or magnetised with an AC waveform to produce a magnetisation pattern at a pitch of, for example, 1.8mm. This final state has the effect of turning the element "off", i.e. preventing it from generating any response in the interrogation field. Each element therefore has four states, and can store 2 bits of data.

The angular gaps between the last two elements 20, 21, and between the last element 21 and the first element 1 are 12 and 16 degrees respectively. All the other elements are at 8 degrees with respect to their neighbours. In a reader system for the tag, the two larger gaps provide a reference mark, so that the elements can be correctly ordered.

The total number of bits that can be stored by the tag is 2x21 = 42 bits. The total amount of useful data that can be stored is slightly less: one bit of data is lost because there is an ambiguity whereby all the elements are magnetised the other way around. In addition, a number of states are not allowed. These are states in which all the elements are turned off (the extreme case), and more generally states in which the first and final two elements 1, 20, 21 are turned off, as this prevents correct identification of the elements. Thus, a conservative figure for the total amount of useful data that can be stored is 40 bits.

The tag is read, in the simplest case, using a rotating magnetic field of around 2.5 kA/m. At this interrogation field, magnetising the film moves the position of the transitions by about 1°.

The tag can be made more compact by placing the lower two rows (elements 1-10) on top of the upper two rows (elements 12-21). This is because the elements above each other are orthogonal.

There are a number of programming methods for the above described tag, starting from a fully demagnetised tag, for example:

1. A gapped "recording head", similar to those used for standard magnetic tape, is used to magnetise the tape;
2. A small permanent magnet is used to magnetise the recording film in either direction. AC magnetisation can be achieved using a magnet with alternate north-south magnetisation;

3. The tag is manufactured initially without recording film. Pre-magnetised film is then stuck onto each element as required; and
4. All elements are programmed in parallel, using a multipole ferrite magnet arrangement: each element is magnetised by a separate ferrite element, with separate coil connections. This permits all four states of all 21 elements to be defined.

In the embodiment described above, the tag stores information by the magnetisation of the bias element above the soft magnetic material. No information is stored in the soft element orientation, amplitude response or coercivity. To increase the data density, one or more of these parameters is varied for each element. Our co-pending application PCT/GB00/03092 describes how these parameters can be read independently, for each soft element.

Alternatively, the same data density can be achieved using fewer magnetic elements. This has many practical advantages. The materials costs of the tag are lower, the tag can be smaller, and the reader system is able to distinguish more tags in the same volume.

For example, using film elements, each element can be made narrower than 9mm (perpendicular to the easy axis). In the simplest case illustrated in Figure 2, two widths are allowed - 9mm and 5mm and first, eighth and ninth elements 1,8,9 are shown with the reduced width. This scheme codes approximately an extra 1 bit for each element. In practice, there are seven states rather than eight since it is not possible to differentiate tags in the off state. If the reading system can discriminate more amplitudes, then more information can be stored as a function of amplitude. The amplitude response can be changed by altering the size of the dipole element. Alternatively, the magnetic bias layer can be used to alter the dipole's effective width and length, by recording AC patterns on part of the film. Mechanical damage of the magnetic material can also be used to alter its effective geometry.

In the examples described above, most of the angular gaps between elements are identical. More data is coded by allowing these gaps to be unequal. For example,

the gaps in the examples above are all 8°. By allowing these to be (for example) 7° or 9°, as shown in Figure 3, an extra 1 bit may be encoded for each element. An upper limit of different states is for example around 4 states – e.g. 6.5°, 7.5°, 8.5° and 9.5°. The design retains the feature of at least one large gap, for example a gap between the last and first elements, larger than any other gap, referred to herein as the "big gap" feature, so that the elements are always read in order. This also means that certain combinations of states (e.g. all with large angles) are not allowed, as the big gap would become too small. This is similar to the data encoding described in publication no. WO99/35610, which is incorporated herein by reference in its entirety. For a simple reader system, the minimum gap between elements must not be so small that the signals from two elements overlap or cannot be distinguished unambiguously. In practice, this means that fewer elements can be used. For example, using the four states above, the tag would be reduced to 17 elements, coding 28 bits of pre-programmed data (by the orientation) and 32 bits of programmable data (by the bias field).

All the elements in the examples described above have the same coercivity (near zero to about 10 A/m). By allowing each element to have a coercivity selected from a set (for example a set of two or a set of four), additional information can be encoded by each element. About 2 bits of additional data can be stored in this way. In practice, the maximum number of elements used is reduced.

In all the described cases, the gain in data capacity is less than the maximum number of states added, because certain states are indistinguishable – for example, those in which elements are turned off by the bias field, but have different amplitude, orientation or coercivity. In addition, most of these alterations lead to reduced number of elements in practice. It will be understood by the skilled person that the various arrangements described above can be combined to provide tags in which data is stored by any two or more properties, for example, a tag in which elements differ in amplitude response, coercivity, orientation and bias.

In a further embodiment, a particularly favourable class of tags can be made from elements selected from a range of available coercivities, and arranged at different

angles to each other. Data is stored primarily by the coercivity of the wire, and by the angles between the wires.

In this embodiment, illustrated in Figure 4, there are 7 magnetic elements 23-29. Each element is a glass-coated amorphous metal wire, 29mm long, with a metal core diameter of around 10 μm, and an overall diameter of around 25 μm, made, for example, by the Taylor-Ulitovsky method. See for example M. Vazquez, A.P. Zhukov : "Magnetic properties of glass-coated amorphous and nanocrystalline microwires" : J. Magn. Mat. 160(1996) 223-228, and J. Gonzalez, N. Murillo, V. Larin, J.M. Barandiaran, M. Vazquez, A. Hernando: "Magnetic bistability of glass-covered Fe-rich amorphous microwire: influence of heating treatments and applied tensile stress": Sensors and Actuators A 59(1997) 97-100. This material is magnetically bistable, with nearly rectangular B-H characteristics and rapid switching characteristics. Alternatively, the elements can be constructed from other forms of wire, ribbon or film, such as cold-drawn amorphous metal wire, for example type 5T, a Barkhausen wire manufactured by Unitaka, Japan. Suitable materials are available from a number of other manufacturers (e.g. Vacuumschmelze, Germany, Allied Signal, Four Winds Inc., USA). In general terms, suitable materials exhibit rapid switching transients in fields changing at more than 100,000 A/m/s, the field level at which these switching transients occur ("coercivity") depends on the material type and a number of different coercivities of material are available.

The elements are chosen from a set of 7 different coercivities in the range, for example, 20-300 A/m. These coercivities are denoted A-G in the following description, with, for convenience, A as the lowest and G as the highest coercivity. The 7 elements are disposed on a substrate 30, at different angles to each other. In the preferred configuration, the elements do not bisect. This is to avoid effects where the tag elements are deformed by all crossing at the same point. The preferred configuration also minimises element-element interactions, and keeps the thickness of the tag to a minimum.

The tag data is stored by a combination of angle and coercivity. For the 7-element embodiment described, the angular separations are used to identify the elements, and to store four decimal digits of data, which form the four least significant decimal digits of the data.

There are six standard allowable angles between any two elements, as follows:

Value	*Degrees*
0	*10*
1	*15*
2	*20*
3	*25*
4	*30*
5	*35*

One gap between elements is required to be bigger than any of the other gaps, referred to herein as the big gap. This can exceed 35 degrees, and is used to provide a datum. The six remaining gaps are split into two halves – three gaps clockwise from the big gap, and three gaps anticlockwise. Not all combinations of gaps are allowed (e.g. all gaps equal to 35 degrees), because the sum of all the gaps in the tag must equal 180 degrees. To maximise the coding scheme efficiency, all combinations of three consecutive gaps are sorted by the total angular space required. A lookup table is generated to convert between the three gaps and position in this sorted list. Combinations of three gaps involving two or more of the smallest gaps are, for example, omitted, as these can be more difficult to decode in a reader system.

Both of the three-gap sequences are converted into positions (numbers) in the sorted look-up table. The coding scheme directs that one of these two resulting numbers is required to be larger than the other (equal numbers are not allowed). The tag is read starting from the big gap, and working through the smaller numbers initially.

The tag elements can be unambiguously identified simply by finding the largest gap, and working out which way round to read the tag – i.e. starting with the smaller of the three gap sequences.

Once the tag elements have been identified individually as described, further data can be stored and retrieved by measuring other specific properties of each element. In the preferred embodiment, this is simply the coercivity of the element. A 7-digit base-7 number can be constructed from the elements taken in a specific order, by assigning A=0, B=1, C=2 ... G=6. For example, the combination of wires ABCDEFG would correspond to the base-7 number 0123456, i.e. 22875 decimal. To generate the complete tag code, this number is multiplied by 10,000 and added to the value from the angular arrangement. There are about 33 bits of data in this arrangement.

The data storage capacity of the coercivity/angle tag described above can be increased in a number of ways. One way to increase the data content is to use more elements. For example, using 9 elements instead of 7, 1,000,000 different angular arrangements can be generated, and 9^9=387420489 states can be stored by coercivity, giving a total data content of about 48 bits.

A further way of increasing data content is to select the wires from a wider range of material types. If there are more types of magnetic material to choose between, then more data can be stored per wire. For example, 8 different states stores 3 bits/wire; 16 states stores 4 bits/wire. It quickly becomes impractical to increase the number of coercivity states above about 20 states. However, many other properties vary between different types of material. For example, certain types of wire show a dependence in switching field on the rate of change of the applied field dH/dt, depending on the conditions of manufacture. This dependence can differ strongly, even for wires of very similar coercivity. Similarly, material switching speeds and switching amplitudes can also vary independently from each other and the coercivity. Switching speeds generally depend on the material construction (for example, glass-coated wire, cold-drawn wire, thin-film and so on), whereas amplitude can also be altered by changing the physical properties of the element, for

example, its length, or for thin-film materials, its width. Each of these differences can be combined to enumerate many more different material types – for example:

Coercivity:	3 bits	(8 coercivities)
dH/dt	1 bit	(e.g. little/large variation)
Speed:	1 bit	(e.g. fast/slow switching)
Amplitude:	1 bit	(e.g. high/low amplitude)

Even with relatively simple discrimination between two states (=1 bit), for each additional property, the data stored by each element can be increased by 3 bits (i.e. approximately doubled to 64 states/element). Applying this to the 7-element tag described above, the data capacity becomes 10,000 x 64^7 = 55 bits. For the 9-element tag, the data capacity becomes about 74 bits. For an n-element tag, with m states per element, the material-encoded part of the tag data is constructed most easily as an n-digit base-m number. This is added to the angle-encoded part in a similar way to that described above.

For tags where elements overlap each other, little data can be stored by adding bias to the tag – this technique is only generally applicable if the elements are physically separated.

Another particularly favourable arrangement is one in which data is stored by a combination of angle and location.

A simple tag consists of a 2D grid, for example, 5x5 locations, 31, as illustrated in Figure 5. A limited number of magnetic elements are arranged on this grid, for example, 7. The elements are disposed at angles relative to each other, in exactly the same way as the coercivity/angle embodiment described above. With 7 elements, about 10,000 different angular arrangements can be stored and each element uniquely identified. The elements can be constructed from a wide range of magnetic wires, ribbons and films. The general requirement is that the element displays a relatively rapid and detectable switching transient in fields changing at more than 100,000 A/m/s. A low-cost embodiment uses 9x9mm squares of soft

magnetic material, for example, Atalante™ thin film material (manufactured by IST of Zulte, Belgium, part number SPR97017A). Any of the materials described above in the coercivity/angle tag embodiment can also be used.

The first element, 32, generally occupies the same point in the grid, for example, the bottom left. The remaining elements can be positioned at any of the remaining sites. For example, with a 5x5 grid and 7 elements, the remaining 24 sites are filled by the remaining 6 elements, giving 96909120 arrangements (about 26 bits). Thus the total tag data capacity is about 40 bits.

Data storage in the location/angle tag described above can be increased in a number of ways. For example, the data content can be increased by using more elements or locations. The penalties of this are that the tag may be larger, or that the reader may require better position resolution to separate out the different location states. Using more elements also increases the tag complexity.

Each tag element can also vary in coercivity, dH/dt dependence, switching speed, amplitude response and bias.

Estimating conservatively:

Coercivity:	3 bits	(8 coercivities)
dH/dt	1 bit	(e.g. little/large variation)
Speed:	1 bit	(e.g. fast/slow switching)
Amplitude:	1 bit	(e.g. high/low amplitude)
Bias:	1 bit	(on/off)

This shows that around 7 additional bits of data (128 states) can be stored per element. For a 7-element tag, on a 5x5 grid, with 128 states/element, the total data capacity is about 89 bits. For a 9-element tag on a 6x6 grid, the capacity can be increased to about 102 bits of data.

It is particularly favourable to manufacture tags with amorphous wire elements where the elements are kept parallel, because this allows the wires to be incorporated into a moving web using standard available equipment. This can also facilitate the use of a simpler reader configuration. Suitable magnetic materials are, for example, bistable glass-coated amorphous metal wires, as described above, or Barkhausen wires.

Figure 6 shows a tag 33, which appears similar to a bar code, constructed from a series of, (in this example) 7 different parallel wires, 34, 35, each 30 mm long, with a choice of, for example, 25 locations at spaced at 2mm intervals, giving a rectangular tag around 30x50mm. The different wire types are used to identify the elements, and data is stored by the location of each element. Using 7 elements, about 26 bits of data can be stored, since one element 34 is assumed to be in a fixed location. Using 9 elements, about 34 bits of data can be stored. Again, data capacity can be increased by selecting the actual elements from a larger pool of available elements, which may differ in amplitude, switching speed or dH/dt variation, or any other measurable magnetic properties.

Combinations of different properties, numbers of allowable states, or numbers of elements are not limited to the embodiments described above. Many factors affect the exact choice of properties to combine in the tag, including the cost of the tag, the size, the required data capacity, the geometry of the reader, the available materials, and the reading environment.

Similarly, the methods used to convert the tag parameters into numeric values are not limited to the methods described in the embodiments above.

Additional discrimination between elements is possible using properties including:

1. Permeability
2. Dependence of switching properties on cross-field bias
3. Barkhausen percentage response as a function of rate of change of field
4. Resonant frequency of magnetostrictive materials

Any of the properties, individually or together with any of the other properties described in this disclosure, can be used to increase the number of states for each element, and hence the total data encoded by the tag.